INNOVATIVE SUBSTATION SOLUTIONS TO REDUCE INVESTMENT COSTS - IMPROVED AVAILABILITY AND RELIABILITY

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1. Summary

This paper describes a modular concept to design, build and operate electrical air insulated substations using integrated Compact switching modules. These modules include all necessary switchgear functions in one pre-manufactured and pre-tested module such as:

- Circuit breaker function
- Disconnector function
- Surge arrester and earthing switch functions

By using integrated modules the following main design advantages are achieved:

- Efficient engineering and shorter project time of different solutions using only a few standardised functional blocks
- Reduction of space requirements, number of foundations and civil works
- Simple and fast installation, connections and cabling.

The Compact substation concept is based on “Reliability Focused Design & Maintenance”. This means briefly to select a solution according to availability studies and removing unnecessary components that may fail or need maintenance (e.g. disconnectors). This paper will demonstrate that with modern low-maintenance modules it is possible to select a simpler substation design without disconnectors and achieve a significant higher availability.

The Compact modules are of a portable “plug-in/ plug-out” design and motorised which means that they can easily be integrated in a Substation Automation or SCADA system. The modules can be rapidly extracted for no-load operations, maintenance, repair or replacement. From the operational point of view this design gives the following advantages:

- A smaller substation with less environmental impact and exposure to lightning, pollution and other severe weather conditions
- Lower failure rate and less maintenance will improve the substation availability
- Fully motorised and automated station will reduce operational costs
- Low-maintenance “plug-in/plug-out” modules will reduce maintenance costs
- Integrated secondary functions and condition monitoring will improve safety (both for the system and the operating staff).

This paper will also describe some typical Compact substations for outdoor and indoor innovative solutions for I-AIS applications (Intelligent Air Insulated Substations) covering the 123 - 800 kV range and I-PDS (Integrated Power Delivery Switchgear) applications covering the 12 - 170 kV range. The described Compact Switchgear modules are fully integrated with protection and control terminals and MicroSCADA with standardised IEC 870-5 protocol.
Finally, a short description of a combined circuit-breaker/disconnector will be presented together with its application in a standardized substation.

RVP-A1/2000 SUB-05 PONENCIA RECOMENDADA POR EL **COMITÉ DE SUBESTACIONES** DEL **CAPITULO DE POTENCIA** DEL **IEEE SECCION MEXICO** Y PRESENTADA EN LA **REUNION DE VERANO, RVP-A1/2001,** ACAPULCO, GRO., DEL 9 A 13 DE JULIO DEL 2001.

2. Introduction - the New Power Market

The objective of the power system is to generate, transmit and distribute electrical energy at required availability, quality and cost with minimum environmental impact and personal hazards. In the deregulated power market, generation, transmission and distribution are three independent blocks where each one has to be profitable. The deregulated markets around the world are slightly different, but in principle the transactions between the blocks are guided by availability, quality and cost of the “product” = electrical energy. If a contracted supply is interrupted the vendor has to pay penalty.

The performance of an installation can consequently be described by its availability, i.e. the ability to deliver the right amount of energy at the right time and with the right price with a minimum safety impact to do so.

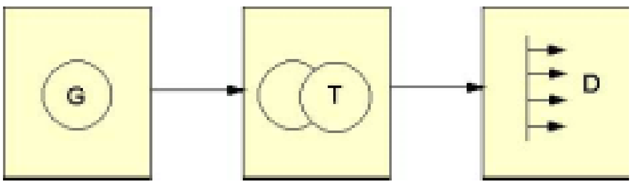

Figure 1. The deregulated power market.

The infrastructure of the new power company, i.e. assets such as generating stations, transformer stations and distribution stations, are valued on the deregulated market not only for what the equipment is “worth” but also for the efficiency and return of capital employed. Consequently low operational and maintenance costs as well as high availability are the most important criteria.

When designing new substations for generation, transmission or distribution, the new approach should therefore be to look at this as a functional solution, not a puzzle of various equipment. The problems for each substation can be summarised in the following examples:

- Generation substation: Connect 100 MW generation to the 500 kV grid with 99.9xxx% availability at a cost of XX USD per MWh
- Transmission substation: Transform 100 MW from 500 kV to 145 kV with 99.9xxx% availability at a cost of YY USD per MWh
- Distribution substation: Distribute 100 MW from 145 kV to 12-24 kV at 99.xxx% availability at a cost of ZZ USD per MWh.

Also for old substations it is important to do a combined availability and cost study. With this it is possible to identify critical functions with high maintenance = costs, time consuming manual procedures = costs and high failure rate/ maintenance rate = low availability. It is important to respect the old saying, “No chain is better then its weakest link”. It is therefore important for a retrofit of a substation to look at the primary as well as the secondary equipment.

We can now define the word “turn-key” in modern way. A turnkey substation today is a turnkey <u>function</u> in a process and is designed and built by functional modules and system components. This turn-key concept does not end with the commissioning but implies that it is possible “to lock” the station and only return when the monitoring system asks us to do so. In the preceding sections we will present Compact Switchgear solutions for I-AIS and I-PDS applications as one way to keep in path with the future.

3. Reliability Focused Design and Maintenance

Design of air-insulated substations has been more or less the same during the last 50 years. This conventional design with individual components of electrical equipment has been based on the use of a large number of disconnectors in order to allow for maintenance and repair with a minimum of interruption. For smaller distribution substations a single busbar arrangement is usually used. For higher voltages or larger substations double busbar systems with by-pass is common.

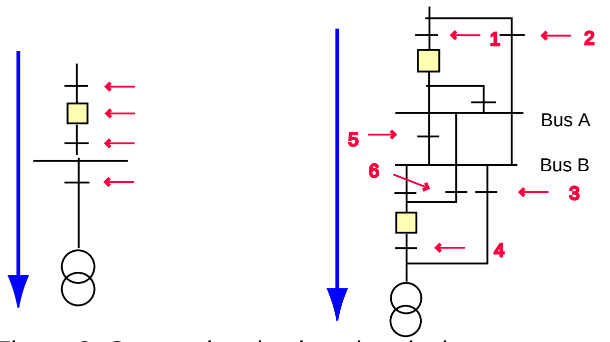

Figure 2. Conventional substation design.

In the single busbar arrangement for distribution a common layout includes one breaker and two disconnectors for the line and one disconnector (or sometimes one breaker and two disconnectors) for the transformer. In order to transmit energy from the line to the transformer all four objects have to be in service. Normally in this type of substation the number of lines and transformers has to be duplicated to improve the availability.

For the double busbar system with transfer switch this arrangement is basically chosen to allow operation during breaker maintenance. (A parallel breaker between bus A and B is used). It is easy to see that when <u>any</u> of the disconnectors 1,2, 3 and 4 has to be taken out of service for maintenance or repair, we will loose the connection between line and transformer. (It is not possible to work on the side of the disconnector which is energised and normally it is not allowed to work at all on this disconnector).

It can also be seen that when the disconnectors 5 and 6 have to be taken out of service for maintenance or repair, we will loose the connection between line and transformer. In order to carry out work on 5 we have to take the line breaker and bus B out of service which means we can not use the by-pass switch. In case of maintenance work on 6 we have to take the transformer breaker and bus A out of operation. We can therefore summarise that although the disconnectors are useful for maintenance and repair of the breaker they can cause a lot of problems themselves. Consequently, an optimum solution with availability to low cost fully depends on the availability of a breaker compared to a disconnector.

The availability can be determined according to well known calculations. The reasons why a connection is interrupted can be divided into failures and maintenance:

- MTBF = Mean Time Between Failure and f= 1/MTBF = Failure frequency
- MTTR = Mean Time to Repair
- MTBM = Mean Time Between Maintenance and m= 1/MTBM = Maintenance frequency
- MTTM = Mean Time to Maintain
- Unavailability = MTTR/MTBF + MTTM/MTBM

The lowest unavailability (and the highest availability) is achieved when the failure frequency, maintenance frequency, time to repair and time to maintain all is minimised.

4. The Compact Concept

Three different evolutionary steps in the design, operation and maintenance of a substation, can be outlined as follows:

- Conventional Design & Conventional Maintenance =
  "If it works don't change it!" = Refuse to change old concepts

- Conventional Design & Condition Based Maintenance =
  "If it works don't fix it!" = Redesign the station but with old layouts

- Reliability Focused Design & Maintenance =
  "If it works make it better" = "Rethink" the power delivery process using new technology.

The conventional design and maintenance is based on the same procedures and experiences of equipment for the last 50 years. Condition based maintenance and remote control/automation have been succesfully introduced as means to decrease operational costs. However, this "re-design" is not changing the primary equipment, only monitoring the same.

In order to take full advantage of the rapid technical development, we need to review the complete functional behaviour of the power process including primary high voltage equipment and secondary measurement, control, protection and monitoring equipment. To do so, we do not need to develop new devices - we need to develop new thinking - the technology is already here!

The reliability and availability of the main component - the circuit breaker- have been continuously improved significantly with SF_6 design and spring operating mechanisms instead of oil breakers with pneumatic or hydraulic mechanisms. Today it is also possible to include controlled synchronised switching in order to reduce the electrical stresses in connection with capacitive or inductive switching and consequently prolong the lifetime. In the same manner polymeric insulators and ZnO surge arresters have significantly improved isolation levels and the surge protection even in polluted areas. The disconnector construction, however, has not been improved correspondingly. In conventional designs the current may be forced to pass through a large number of disconnector contacts and due to maintenance or failure of the disconnector current paths they can be out of service for longer or shorter periods. Hence, the disconnectors are playing a vital role when calculating the availability of a substation.

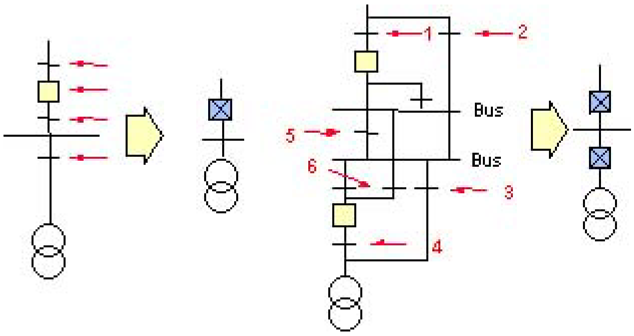

Figure 3. The Compact concept.

In the Compact substation Reliability Focused Design and Maintenance is used throughout the process. This means briefly to select a technical solution based on availability calculations and limit unnecessary components with substantial failure rate and maintenance requirement as much as possible. By replacing the conventional breakers and disconnectors (and optionally instrument transformers, surge arresters and earthing switches) with a motorised "plug-in/plug-out" module the availability will be maintained and in most cases significantly improved with a lower life cycle cost as a result.

5. Compact Switching Modules

The Compact modular range covers 12 - 800 kV applications. Here we will more in detail describe two modules as typical examples. An EHV Compact switching module (362 - 800 kV) and a HV switching module (72,5 - 245 kV). In addition, a line entrance module can be combined with any of these switching modules for 72,5 - 800 kV, and consequently, it is possible to design and build any 72,5 - 800 kV substation by using three different types of modules only.

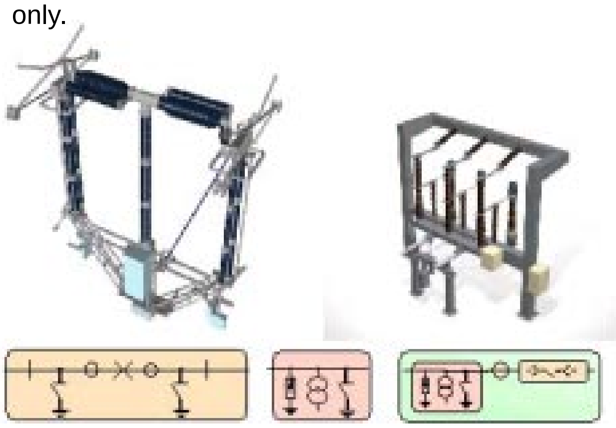

Figure 4. Switching Modules.

Switching Module for EHV (HPL Compact with one "plug-in/plug-out" module per phase) with options:

- Standard SF_6 circuit breaker with spring operating mechanism
- Two pantograph motor operated disconnecting functions per phase
- Two motor operated earthing switches per phase

LTB Compact.

Switching Module for HV (LTB Compact with one "plug-in/plug-out" three-phase module for 72,5 - 170 kV and three one-phase units for 245 kV) with the following options:

- Standard SF_6 circuit breaker with spring operating mechanism
- Motor operated truck with two maintenance free disconnecting functions per phase
- One motor operated earthing switch per phase
- One conventional CT per phase
- One Surge arrester with polymeric insulation per phase
- Gantry with busbar on top for 90 degree or 180 degree connection.

Line entrance module for HV and EHV with the following options:

- One VT per phase
- One motor operated earthing switch per phase
- One Surge arrester with polymeric insulation per phase

6. Compact for 500 kV

For transmission substations the "Breaker-and-a-half" configuration is the normal design in most countries. The advantage with this scheme is that any breaker or one of the two busbars can be taken out of service without interruption. The main disadvantage is a relative large substation with high investment and operational/maintenance costs.

With the Compact modular concept it is possible to replace the conventional disconnectors by integrating one pantograph disconnector on each end of the circuit.breaker module. This allows the design of a "Breaker-and-a-half" station by combining these switching modules with line entrance modules on an area which is reduced with almost 50% to that of a conventional station. In addition, the maintenance costs are significantly reduced and the complete module (with breaker and disconnector functions) can be shifted and/or replaced during maintenance/repair.

HPL Compact

7. Compact for 145 kV

For a 145 kV station the LTB Compact module includes the busbar so that several modules can be simply joined together to form the substation. In this manner a single bus switchgear for two lines and two transformers can be built inside an area of 28 x 14 sq.m using 4 LTB Compact modules and 2 Line Entrance modules.

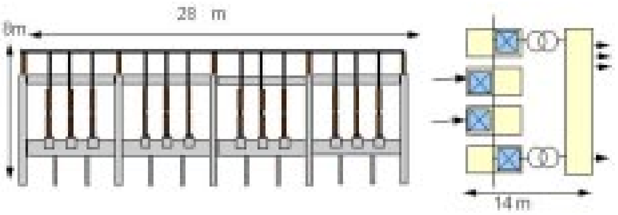

Figure 5. Compact 145 kV station with 2 lines and 2 transformers.

With the LTB Compact modules it is possible to design power transformer substations (or generating substations) from one transformer to several feeding transformers. The designs include single bus, ring bus and double bus which all have improved availability compared to a conventional design. The double bus can be extended to a large number of transformers and lines. The lines and transformers are divided between the two busbars in order to obtain maximum availability.

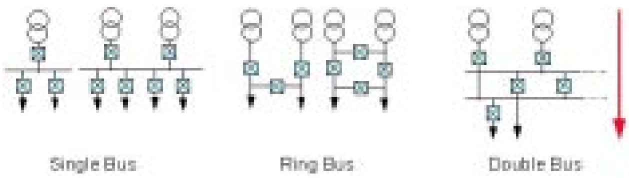

Figure 6. Different 72 - 245 kV LTB Compact configurations.

The Compact module can be "plugged in/plugged out" using the motorised truck. This can be done for temporary disconnection, for maintenance at another location and for emergency repair. If a spare unit is available the time for replacement is basically 1 hour + the handling and transportation time. The modules are interchangeable so in case of maintenance work on one module it is possible "to borrow" a module from a less critical spot. It is finally possible to save the cost of a complete Compact module and only install "empty truck positions".

For a 500 kV substation described under section 6 above we can now design the 145 kV side and the best solution is a double bus with one transformer connected to each bus. When two lines are feeding the same substation they will also be connected to different busbars.

There are no disconnectors in the station and the availability is therefore very high.

With the Compact modules it is possible to design power delivery substations from one line/one transformer to four lines/four transformers. In order to improve availability only Compacts are used. The "H-connection" with 3 Compact modules gives the highest availability at the lowest costs. For a large substation with 4 transformers it is possible to divide the busbar with two transformers connected through disconnectors to each busbar and thus maintaining high availability - if the transformers are interconnected on the MV side - since half of the substation can be taken out of service while maintenance is carried out on the disconnectors.

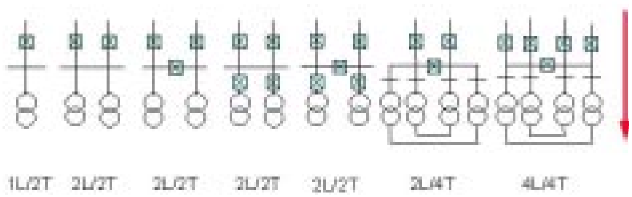

Figure 7. Different LTB Compact configurations for 72 -170 kV power delivery systems.

8. Compact for URBAN

It is also possible to build indoor Urban substations using standardised LTB Compact modules. The Urban concept includes completely enclosed substations or semi-enclosed (only switchgear) when the transformers are outside (but hidden behind walls).

- Pre-manufactured and pre-tested design ensures reliability
- Each cell is separated from the transformers and MV switchgear minimises failure risk/ consequences
- Pressure relief protection in case of an indoor short circuit and optional infra red ultra high speed detection
- Transformers can be placed indoor or outdoor (behind walls)
- LTB Compact is easily accessed/removed through doors in the front
- Personal safety protection when the doors are opened
- Very small dimensions (width, length and height)

The modular concept can easily be extended when more lines and/or transformers needs to be connected.

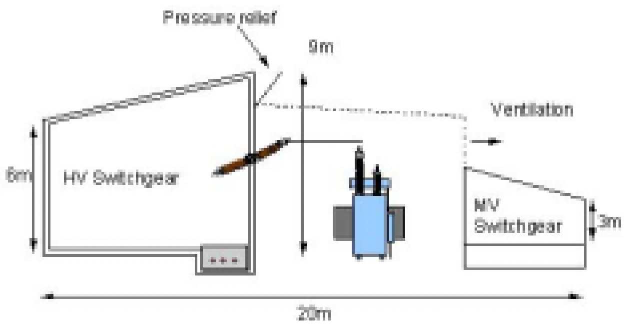

Figure 8. Side view of a Urban 145 kV substation.

For an Urban substation with cable entrance it is possible to build a very compact substation for two lines and two or four transformers as shown in figure 10.

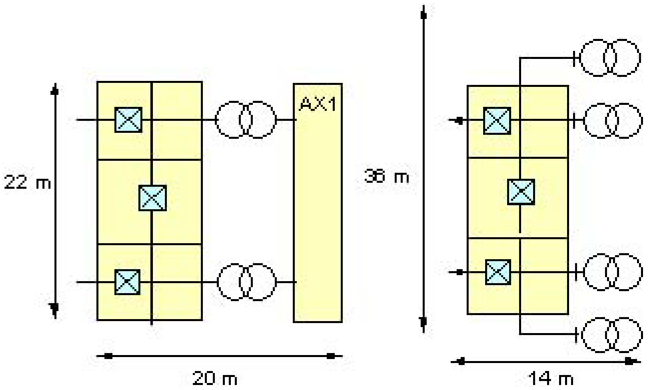

Figure 9. Urban substation for cable entrance.

For a overhead line entrance it is necessary to use a wall bushing entrance (or a cable from the line entrance). It is however still possible to hide the bushing entrance coming in from above as shown in figure 11.

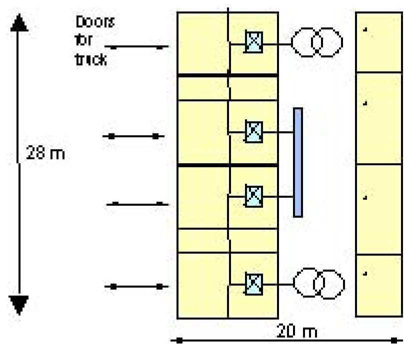

Figure 10. Urban with 2 line entrances and 2 cable entrances.

9. Combined circuit-breaker disconnector

The Combined unit is a disconnecting circuit breaker based on the ABB circuit breakers LTB and HPL.It is a combination of a disconnector and a circuit breaker, which fulfills all requirements for a circuit breaker as well as for a disconnector. The disconnector function is carried out by the circuit-breaker main contacts. In open position, the contact gap has the insulation level required by the ANSI and IEC standards for disconnectors. LTB and HPL Combined therefore replace conventional combinations of separate circuit breakers and disconnectors. Furthermore, the combined unit is equipped with a motorized earthing switch.

A simple and compact substation layout with highest availability and lowest maintenance demand is then obtained.

Visual indication of the open position and earthed contact together with an interlocking system ensures personal safety.

Combined is available for voltages in the region 72.5 - 145 kV (with LTB) and 170 - 420 kV (with HPL).

A disconnecting circuit breaker must be equipped with a safe and reliable system which prevents maloperation and indicates the contact positions. The system shall prevent that the circuit breaker and the earthing switch is closed against an energized circuit.

LTB Combined

For Combined, this is carried out as a logic chain with a key exchange system. Indicators such as signs, lamps and position of the earthing switch, if applicable, shows when the circuit breaker is locked in the open position. Furthermore, each breaker pole is equipped with a directly connected ”Open/Closed” sign.

Another safety feature is the use of polymeric insulators, which, beside their excellent electrical properties, also are tolerant towards mechanical stress and damage.

The disconnecting circuit breakers replace conventional combinations of breakers and disconnectors in many different substation layouts. A substation that is simplified in this way have comparable, or even better, availability than one with conventional breakers and disconnectors. The main reasons are reduced maintenance requirements and lower risk of equipment failure, due to reduced number of disconnectors.

Figure 11a and 11b shows how a conventional double busbar scheme can be replaced with a combination of Combined and a Compact switching module. Here, three conventional disconnectors are eliminated in each line and transformer bay.

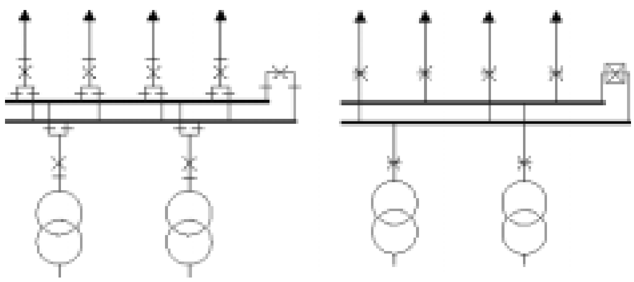

Figure 11a. Conventional layout. *Figure 11b. Layout with Combined and Compact.*

Disconnecting circuit-breaker
Withdrawable Switching module
Circuit-breaker
Power transformer
Disconnector

The main features can be summarized as follows:

- Pre-manufactured multi-function module
- Integrated SF_6 breaker and disconnector function
- Pollution & explosion resistant composite (polymeric) insulation
- Simplified station layout without disconnectors

The most important benefits are:

- Fast and simple installation at minimum area
- Reduced operating and maintenance costs
- Maximum personal and equipment safety
- Maintained or improved availability with lower costs
- Reliable, accurate & secure measurement, protection & control system.

10. PS 1

PS 1 (Productified substation) is a substation concept up to 145 kV built up by one or more of the following standard innovative solutions:

- Combined circuit-breaker / disconnector (Please refer to section 9 above).
- Standardized GIS switchgear
- Standard optimized power transformer
- Intelligent medium voltage switchgear

There are seven standard HV configurations for substations (please refer to fig.13).

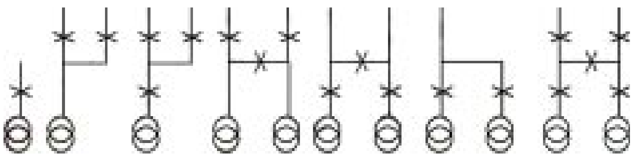

Figure 12. HV configurations in PS - 1 Substations.

The same reliable functionality for the PS-1 substations are guaranteed as for traditional system solutions. The functionality of a PS-1 substation is equal to a typical distribution substation with up to two connected high voltage lines, a maximum of two power transformers and up to twenty medium voltage outgoing feeders.

Due to the complete standardization of all process steps and the entire equipment, a PS-1 substation project can usually be completed in half the time compared to a traditional conventional project.

The consistent realization of the PS-1 concept has resulted in a turnkey system which sets new standards for the future, while offering a cost advantage of up to 20 % as a standard unit in comparison with substation solutions tailored to fit detailed customer specifications.

11. Conclusions

In EHV applications in the voltage range 362 - 800 kV, HPL Compact in a “Breaker-and-a-half” or ringbus scheme results in a substation that requires much less space than a conventional one and in addition higher availability with lower life cycle costs.

In HV applications in the voltage range 72 - 245 kV, LTB Compact modules which includes the busbars as an integral part, results in a flexible solution where several modules easily can be joined together to form the substation. This allows for “re-engineering” of the substation replacing a complex substation layout with a compact and simple design. The result is a smaller substation which is less exposed to severe weather conditions and a shorter busbar will reduce the mechanical stresses during a short circuit. Furthermore the control and protection system of the substation can be done more simple.

In the I-PDS concept the LTB Compact (HV) and AX1 Compact (MV) are integrated with the REx5xx series protection, monitoring and control terminals connected to MicroScada providing a complete station automation solution. For Urban solutions this can be done indoors. All this will naturally give a more economical solution but also increase the availability of the substation. Additionally, from the environmental point of view, a small and beautiful substation can be realized that fits in very well with the existing sourroundings.

Finally, PS 1 and Combined are excellent examples of the new thinking and approach in realizing future substation projects. Also our role as “conventional engineers” are changing into new roles where we have to focus more on a combination of both technical and financial engineering.

12. References

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